MINERALOGY AND ORIGIN OF THE TITANIUM DEPOSIT AT PLUMA HIDALGO, OAXACA, MEXICO

by

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(1961)

SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE
DEGREE OF MASTER OF
SCIENCE
at the
MASSACHUSETTS INSTITUTE OF
TECHNOLOGY
May 18, 1962

Signature of Author . .
Department of Geology and Geophysics, May 18, 1962

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Abstract

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"Submitted to the Department of Geology and Geophysics on May 18, 1962 in partial fulfillment of the requirements for the degree of Master of Science."

The Pluma Hidalgo titanium deposits are located in the southern part of the State of Oaxaca, Mexico, in an area noted for its rugged terrain, dense vegetation and high rainfall. Little is known of the general and structural geology of the region. The country rocks in the area are a series of gneisses containing quartz, feldspar, and ferromagnesians as the dominant minerals. These gneisses bear some resemblance to granulites as described in the literature. Titanium minerals, ilmenite and rutile, occur as disseminated crystals in the country rock, which seems to grade into more massive and large replacement bodies, in places controlled by faulting and fracturing. Propylitization is the main type of alteration.

The mineralogy of the area is considered in some detail. It is remarkably similar to that found at the Nelson County, Virginia, titanium deposits. The main minerals are oligoclase - andesine antiperthite, oligoclase-andesine, microcline, quartz, augite, amphibole, chlorite, sericite, clinozoisite, ilmenite, rutile, and apatite.

It is proposed that the ore mineralization is due to replacement of the country rock by titanium bearing hydrothermal solutions. Many questions remain unanswered and it is hoped that research in the area will be carried further.

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Acknowledgements

The author wishes to thank Dr. Joseph L. Gillson for his guidance in the preparation of this thesis, and for his unfailing interest in its subject. Dr. Gillson read and criticized the manuscript before it was submitted in its final form. Thanks are also due to Mr. E. F. Fitzhugh, jr., of the Republic Steel Corporation, for generously providing maps and information on the area; and to Mr. David Marks, who assisted the author in the field.

Foreword

The following paper is a preliminary study of the rocks and titanium ores of the Pluma Hidalgo area in the State of Oaxaca, Mexico. It deals mainly with the mineralogy and petrology of the area. The author believes that it is the only detailed study that has been made of the area, although geologists of the Republic Steel Corp. have mapped the general geology.

The polarizing microscope was the only tool used in the analysis of thin sections and powders. Certain features of the samples from the area--especially their extremely fine grain and their great degree of weathering and alteration--made the polarizing microscope not as ideal a tool of research as it would be under even slightly better conditions. Due to certain limitations, no chemical or spectrographic or other means of analysis could be carried out, but any further studies should certainly include these means. Also, any further studies should strive for a better understanding of the field relations and of the regional geology. The time spent in the field, five days, was used for obtaining representative samples, and was inadequate for detailed mapping, due to the deep weathering and heavy vegetation cover.

Chapter I

Introduction

Location of area

The area under study is located near the town of Pluma Hidalgo, State of Oaxaca, Mexico, approximately at latitude 15° 55' N. and longitude 96° 25' W., or about 130 kilometers due South of Oaxaca City. (See maps).

The main titanium orebody, and the one from which most of the specimens for study were taken, is known as the Mina Tisur. It is located about a half-mile west of Pluma Hidalgo.

Pluma Hidalgo was reached by car by travelling on the all-weather (asphalt and gravel)road from Oaxaca City to Puerto Angel as far as Copalita (about Km. 200). At Copalita there is a branch road to Pluma Hidalgo, about 14 kilometers away. This branch road--and indeed all the roads in the area except the main highway--is narrow, muddy, very rutted and has many steep grades. It should be attempted only in a double-traction vehicle, especially during the rainy season. The trip from Oaxaca City to Pluma Hidalgo takes about five hours--four hours to Copalita and about one hour for the last 14 kilometers.

Alternate ways of reaching the deposits include flying by small plane from Oaxaca City to either Finca Dolores (10 kilometers from Pluma Hidalgo) or Pochutla (26 kilometers south of Pluma Hidalgo), and completing the journey by jeep.

Pluma Hidalgo is a town of about 4000 people, and it serves mainly as a supply center for the surrounding coffee "fincas" or plantations. The

town has a church and a school. Hotel facilities, as such, are non-existent. However, bed and board may be obtained from one of the local merchants, Don Aurelio Silva.

History

The deposits were discovered in 1939 by one Sr. Carlos J. Leyva of Pluma Hidalgo. After taking several samples of ore to the Instituto Geológico de México, and learning what he had found, he denounced various areas. However, the claims were not worked.

In 1953, the Republic Steel Corporation took an interest in the area, and eventually the Corporation's claims extended from Pluma Hidalgo to Apango, covering an area of about 20 square miles. An extensive exploration program was started, along with development work on an underground mine in the main orebody west of Pluma Hidalgo. However, with the eventual realization that the amount of ore was not as great as had at first been thought, coinciding with a fall in the market price of rutile, operations ceased in 1957.

Climate

Pluma Hidalgo is located in the Sierra Madre del Sur mountain chain, a formation of extreme relief which acts as a natural barrier to the hot, humid air from the Pacific Ocean and traps most of it. The area is thus characterized by much rainfall. The "wet" season, with nearly constant heavy rains, occurs from May to mid-November. The other months have variable rains, with late December and January being the driest. Rain is not uncommon during these "dry" months, but it is apt to be a short-lived afternoon

shower rather than a twelve-hour downpour as is common in the other months. Reportedly, total yearly rainfall has been as much as ten meters, but five meters is typical.

The vegetation is of the rainforest type--dense, tropical and subtropical plant life, with vines, heavy brush, and a thick overhead covering. There are some notable examples of the so-called "strangling-fig," which eventually "strangles" its host tree. Trees are large and tall, and they often grow so close at their tops that very little light reaches the ground. Partly because of this natural overhead protection, the region is well suited for growing coffee and is indeed the third largest coffee-raising area in Mexico.

Topography

The Pluma Hidalgo area is located on the Pacific side of the Sierra Madre del Sur, the summits of which rise over 10,000 feet. It is an area of extreme relief and rugged terrain, often much more so than topographic maps would indicate. These maps, made from aerial photographs and supplied to the author by the Republic Steel Corp., are at times contoured for the tree-top topography rather than the ground, which tends to be much more accented. It is an area of high mountains and deep gorges and ravines. Landslides are common during the rainy season, and the roads must constantly be kept clear of debris.

The highest point in the area is the top of the Cerro Espino, a limestone mountain 4575 feet above sea level. It is only about three miles from the lowest points in the area, elevation 1000 feet, on the rivers Toltepec and Magdalena on either side of the "cerro." The town of Pluma Hidalgo is at an elevation of 4365 feet.

The area is drained mainly by three rivers: the Rio Magdalena, the Rio Toltepec, and the Rio Chacolapilla, with its large tributary stream, Rio Pluma, which passes by the main ore deposit. There are many small mountain streams.

References to the Deposits

Literature on the deposits is very scanty. They are mentioned by Gillson[1*] (1949), by Gonzalez Reyna[2] (1956), and in Lynd[3] (1960) by T. P. Thayer of the U. S. Geological Survey, who gives the fullest and most accurate description. Dr. Thayer presents only a short and undetailed summary of his observations and conclusions, but they agree, in essence, with those of the author.

*Numbers refer to the notes which are found on Pages 49-52.

Chapter II

Geology of the Area

I-General Remarks

With the exception of a few limestone areas, notably the Cerro Espino, and a variety of dike rocks, the country rock of the area consists, as far as is known, entirely of a series of feldspar-quartz gneisses, commonly with ferromagnesian bands. The attitude of foliation of the rocks, as shown by quartz and ferromagnesian bands is remarkably consistent in the area, nearly always striking northwest and dipping steeply.

The age of the rocks is probably not known accurately. The Carta Geológica de la República Mexicana (México, D. F., 1942) maps the region as pre-Cambrian, as does the Geologic Map of North America (Geological Society of America, 1946). However, the most recent geologic map, Carta Geológica de la República Mexicana (Comité de la Carta Geológica de México, México, D. F., 1960), maps the region as Paleozoic metamorphic and shows a large area of Paleozoic granitic intrusives just south of Pochutla, which is about 20 kilometers south of the area. Cerro Espino is a Cretaceous limestone. No published literature seems to be available on the subject of age.

The area is poor in outcrops of fresh rock. The feldspar-rich country rock alters easily to a soft, clay-like material which can be sampled more easily with a shovel than with a geologic hammer. More often than not, the road-cuts will expose this clay-soil, which varies in color from white to deep red, depending on the amount of ferromagnesian minerals in the original rock. Furthermore, a thick sheet of soil and dense vegetation covers most

of the area. However, good samples can be found in streams. Drill cores obtained at the mine site yielded specimens of fresh rock, and these were used extensively and advantageously for thin sections.

II-Structural Geology

The structural geology of the area is not well known. However, it can be said that the attitude of foliation, in the form of quartz bands, stringers, and lenses, and ferromagnesian bands, is very consistent. The strike of the foliation bands ranges from N 40° W to about E - W, varying only locally throughout the area. The indicated extremes are rare, and by far the great majority of the strikes fall between N 60° W and N 80° W.

The dip of the foliation bands ranges between 50° S and 50° N, again varying only locally. By far the great majority of the dips is within 5° of the vertical.

Faults are quite common in the area. Their attitude varies widely.

It should be noticed that the orientation of the long axis of known areas of high titanium mineralization[1], as well as the general trend of the line connecting these areas, coincides with that of the foliation. (See Map #2). The same phenomenon can be seen on a minor scale in that ilmenite, a common mineral in the country rock, is very intimately associated with the ferromagnesian bands.

At the Pluma Hidalgo deposit, numerous faults and fractures, many with strikes close to that of the foliation, have controlled much of the rutile mineralization and some of the ilmenite mineralization. Thus, rutile is often concentrated at and near fault planes, becoming less concentrated with increasing distance from the faults, which are assumed to be feeder channels for the mineralizing solutions.

III-Petrography

Country Rock- The country rocks are a series of gneisses consisting of feldspar, quartz and ferromagnesian minerals. Except locally, feldspar makes up most of the rock, but there may be as much as 30% quartz and 40% ferromagnesians (Figures 1-4). Very locally ferromagnesian minerals may predominate and make up most of the rock. Again very locally, the rock may be all feldspar.

The feldspar and ferromagnesians are fine grained. The feldspar is very pure white, although altered to clinozoisite and sericite in most places, and it commonly assumes a chalky appearance, presumably due to surface weathering. The ferromagnesian minerals are various shades of green, apparently depending on the amount of chloritization which has occurred. The quartz is in the form of bands, lenses, and stringers, generally up to about ½" wide, but varying in length and width. It is generally crushed.

The ferromagnesian minerals are primary augite and primary hornblende, with augite altering to hornblende and both altering to chlorite. Olivine is not common but was noted in some samples. Locally, small garnets may be present in either a feldspar or a ferromagnesian matrix or both. Ilmenite, often with apatite, is a common, though minor, constituent.

The feldspars consist of plagioclase of oligoclase-andesine composition (An_{28} - An_{32}, varying locally) and, in lesser amounts, the potash feldspar microcline. These may be present as microantiperthite where the blebs of exsolved[2] material are microcline and the groundmass is plagioclase, the former generally making up 20 - 40% of the total. More commonly, the

two feldspars are present as separate grains, the plagioclase grains being more numerous as well as larger than the microcline grains. As far as can be determined, the compositions of the antiperthetic plagioclase and the granular plagioclase are the same. It is thought that the original rock, consisting essentially of antiperthite with some quartz and ferromagnesians has undergone regional dynamic metamorphism with the right conditions of heat, pressure, and rate of cooling to segregate the quartz in the form of bands of constant orientation (i.e., to a form gneissic structure), and to recrystallize the feldspar largely as separate minerals rather than antiperthite. The amount of antiperthite which remains in the country rock varies, but in most slides examined is less abundant than the recrystallized feldspars, and most grains exhibit some bending and strain as shown by undulatory extinction.

The country rock does not correspond in composition to any of the common igneous or metamorphic rocks. If necessary, for purposes of classification, since it usually contains over 5% quartz and dark minerals, and since the plagioclase is greater than potash feldspar, the rock could be called a granodiorite gneiss. On the other hand, where quartz and ferromagnesians are low, the composition of the rock approaches that of the host rock for titanium mineralization at Nelson County, Virginia. This rock, called an anorthosite by Ross,[3] contains andesine antiperthite as possibly the only primary mineral. Similarities between the Pluma Hidalgo deposit and the Nelson County deposits are discussed more fully in Chapter III.

In both appearance and mineral content the country rocks of the Pluma Hidalgo area are similar to certain "acid" assemblages of the metamorphic granulites and their igneous equivalents, the charnockites,[4] as found in Uganda, Ceylon, and Finland. Most authors divide the rocks into "acid," "intermediate" and "basic" groups. Groves described the "acid"group from Uganda as being poor in garnet, unlike most granulites. One "acid" specimen was described as a:

> . . . genissose granite with hypersthene (rather pale in thin section), diopside, hornblende, and dark mica as the mafic constituents. The plagioclase is a basic obligoclase accompanied by some antiperthite. Large patches of feldspar devoid of twin lamellae (part of which must be orthoclase) occur, together with quartz. The latter has peculiarly shaped geometric outlines and also occurs as rounded blebs in feldspar crystals. Both dark mica and apatite are more abundant than usual.[5]

The normal analysis of the rock described above follows:[6]

quartz	23.70%
orthoclase	30.02
albite molecule	20.44
anorthite molecule	11.12
diopside	3.66
hypersthene	8.85
magnetite	0.23
ilmenite	1.22
apatite	0.34

Adams described one acid type of charnockite from Ceylon as:

> . . . dark greenish-gray in color and fine in grain . . . showing indistinct foliation, which structure is visible also in thin section . . . It is composed largely of quartz and feldspar . . . The dark color of the rock is due not to the prevalence of femic minerals but to a multitude of minute dark inclusions present in the salic minerals.[7]

The normal analysis for the rock just described is shown in the first column of the following table. In the second column is the normal analysis for another rock in the same group, but slightly more basic.[8]

	I	II
quartz	29.46%	23.70%
orthoclase	20.02	30.02
ab molecule	23.58	20.44
an molecule	11.68	11.12
hypersthene	5.84	8.85
diopside	-	3.66
magnetite	1.39	0.23
ilmenite	5.02	1.22
apatite	2.02	0.34

The outstanding features of the above analysis from other areas are that the feldspar is the dominant mineral, greater than quartz or ferromagneisians, and that in most places the plagioclase is greater than or about equal to the orthoclase. Titanium is high; ilmenite is greater than magnetite. Apatite is common.

Eskola described granulites from Lapland. In general, "the Lappish granulites are banded garnetiferous quartz-feldspar rocks with bands of more basic, mostly garnet-free and hypersthene bearing material."[9] Again, the rocks vary from light, acidic types to ultrabasic. They are considered metamorphic.

A survey of the common minerals in these rocks shows that the plagioclase in the acid types is generally between An_{25} and An_{30}. In the slightly more basic types, containing some hypersthene, the plagioclase is andesine, commonly antiperthitic.

Garnet content varies from sparse garnets in the light, acid type (which contains little biotite); to large (up to 2 cm.), well developed garnets in the more common field or granitic granulite with plentiful biotite; to no garnets in the noritic and ultrabasic granulites, composed of plagioclase and peridotite-pyroxene.

Ilmenite is commonly associated with the basic bands, though it is rarely greater than magnetite, while rutile occurs in the acid phases.

Apatite is "a common minor constituent in garnet-free intermediate and basic granulites. Its almost total absence in acid granulites is striking."[10]

The analysis presented by Eskola vary a good deal, though in nearly all of them the plagioclase is greater than the orthoclase. Feldspar is generally the dominant mineral, greater than quartz and ferromagnesians. Titanium minerals and apatite are greater than normal.

These facts, together with the above analysis, are presented to show certain similarities between these rocks and the rocks at Pluma Hidalgo.

Of course, there are striking differences too, notably the common occurrence of hypersthene and garnet in granulites. Also, only one distinct assemblage, namely the acidic, is comparable. Not enough work has been done to draw any conclusions or to decide if the similarities are at all meaningful.

Alteration

The principal minerals in the country rock show alteration as follows: feldspar to sericite and clinozoisite (Figures 12 and 13), augite to hornblende to chlorite, hornblende to chlorite, ilmenite to leucoxene. It is not possible to tell how much of the sericitization and chloritization is due to meteoric waters and how much is due to hydrothermal solutions. It is proposed that the clinozoisite and much of the sericite and chlorite are due to a type of propylitization. This subject is discussed fully in the pages following the description of the ore, as the alterations are often better developed and more obvious in the mine rock, which has not been as affected by surface weathering.

Ore - Economic considerations aside, the dividing line between country rock and ore is indeed an arbitrary one. It has been stated that ilmenite is a very common, though usually minor, mineral in the country rock, being almost always associated with the basic bands. Also, rutile is found disseminated as small crystals in the feldspar. From a country rock barren of titanium minerals to a rock which can be called "ore," there are are any number of gradations. For purposes of describing ore, the

following arbitrary divisions are made.

1) ilmenite gneiss: a rock containing more than 5% ilmenite, with the rest of the rock consisting of feldspar, quartz, and ferromagnesian minerals. The feldspar is a mixture of oligoclase - andesine and microcline, as separate crystals and as antiperthite, as described before. The ferromagnesians are mainly augite, hornblende, and chlorite. The ilmenite follows the foliation of the rock and is associated with the ferromagnesians. Apatite is a common accessory mineral.

2) disseminated rutile ore: a rock containing 1% to 10% rutile as disseminated crystals, commonly in feldspar but in places in the ferromagnesian part of the rock. The rock usually contains quartz. Ilmenite may or may not be greater than 5%, but it is almost always present. The rutile crystals are well developed, in places as large as ¼". See figures 6-8.

Less commonly, the rock may be predominantly basic, containing feldspar (mostly antiperthite) in the form of what appear to be inclusions (possibly porphyroblasts) which are cut and often "soaked" by chlorite (Figure 5).

3) concentrated rutile ore: a rock containing massive rutile in quantities greater than 10%, and either a feldspar or a ferromagnesian groundmass, with or without ilmenite greater than 5%. The rutile is well developed. Crystals as large as 1" were seen. The feldspar in this rock often appears to be "soaked" and largely replaced by chlorite. This rock was considered by Republic Steel to be high-quality ore[11] (Figure 9).

These three types of ore (as well as barren rock) are found at the main deposit west of Pluma Hidalgo. The ilmenite gneiss and the disseminated rutile are fairly widespread over an area measuring about 2000 feet by 1000 feet, while concentrated rutile occurs locally and seems to have been controlled by faulting and fracturing. Likewise, the deposition of the disseminated rutile was controlled by fractures, but they are minute and obvious only with the aid of the microscope.

The same general types of mineralized rocks are found also in the designated areas on Map #2.

Alteration

Alteration of minerals in the ore is common, although its degree and intensity is subject to local variation.

Sericite begins to replace the granular oligoclase - andesine and microcline before attacking antiperthite, and of these microcline first. Thus granular feldspar is generally more altered than antiperthite. Since the alteration normally begins in the interstices of the material, this may be explained by the fact that the granular feldspar has more surface between grains (the antiperthite grains commonly being larger). When attacking antiperthite, sericite attacks microcline first (Figure 15). Sericite may often be so well developed that it can be called muscovite. Nowhere was sericite seen attacking the ferromagnesian minerals, as may happen in a case of severe sericitization[12].

Clinozoisite (iron-free epidote) replaces the feldspars, but unlike sericite, attacks the plagioclase before the microcline (Figure 14). It

attacks granular plazioclase and antiperthitic plagioclase with equal ease. It is often seen as veinlets (Figure 17).

Augite alters to hornblende, which alters to chlorite (Figures 19 and 20). Primary hornblende also alters to chlorite. There are several kinds of chlorite, probably including antigorite, which is a type of serpentine as well. The type of chlorite which is present depends on the nature of the mineral from which it was derived as well as the nature of the altering solutions. The different chlorites are discussed more fully in Chapter III. Chlorite is seen replacing feldspar, both intersticially and in veins (Figure 24), in most places near ferromagnesian minerals. It is occasionally seen replacing quartz. Pyrite may be present as minute grains in the chlorite (serpentine ?), but this is not common.

Biotite alters to a chlorite which is probably penninite.

Apatite is replaced by calcite in a few places (Figure 21). However, calcite is not a common mineral.

Rutile and ilmenite may alter to sphere and leucoxene (Figure 25).

The alteration described above is similar to propylitization, although this term has, as a rule, been applied only to volcanic andesites but sometimes to other basic rocks (for example, the basalt flows at Keweenaw Peninsula, Michigan). The term became common after it was applied to the hydrothermal alteration of andesites at the Comstock Lode, Nevada.

Schwartz, in a review of hydrothermal alteration of igneous rocks, states that the important criterion for propylitization is the formation of chlorite and epidote as alteration products. He quotes Kemp as stating that carbonates are also essential[13]. Lindgren quotes Rosenbusch on the subject as follows:

> The characterisitc features of propylitic facies consists in the loss of the glassy habit of the feldspars; in the chloritic alteration of the hornblende, biotite, and pyroxene (often with an intermediate stage of uralite), with simultaneous development of epidote; further, an alteration of the normal groundmass into holocrystalline granular aggregates of feldspar, quartz, chorite, epidote and calcite, and in a considerable development of sulphides.[14]

The sulphide is usually pyrite, Lindgren adds. However, Coats agrees with Von Inkey, whom he quotes as stating that pyrite (sulphide) is not essential to propylitization.[15]

At Comstock, according to Lindgren, propylitization is characterized by augite changing to chlorite, which infiltrates the feldspar. Coats adds that the hornblande changes to chlorite with calcite and magnetite, and that the feldspar goes to albite and epidote.

Reber describes propylitization at Morenci, where the process developes the following minerals: serpentine, hornblende, tremolite, epidote, magnetite, calcite, chlorite, biotite, talc and sericite.[16] He believes that propylitization is a less intense phase of sericitization. In the outlying portions of the Morenci District, porphyry and diabase occur together, and the hydrothermal alteration on each is compared:

> The sericitic alteration which is universal in the mineralized portions of the porphyry changes a rock consisting of plagioclase, quartz, and occasional biotite phenocrysts, and a fine-grained granitic groundmass of

quartz, orthoclase, and alkali plagioclase to a finely felted aggregate of quartz and sericite.

. . . in the highly sericitized rock, no trace of biotite remains. Less thoroughly sericitized specimens . . . always show the biotite bleached or more or less completely altered to chlorite.

This development of chlorite is clearly related to the propylitic type of alteration, and occurs here as a less intense phase of sericitization.

The diabase dike rocks, the alteration of which is believed to be correctly classified as the propylitic type, were originally composed largely of labradorite and augite. In the more altered rocks the labradorite is not entirely gone, though it is somewhat sericitized and encroached on by the serpentine resulting from the alteration of the augite. The augite is changed to hornblende or more completely altered to actinolite and serpentine.[17]

Reber defines propylitization as any alteration of igneous rocks in which hydrous magnesian alteration products are important and are associated with epidote and carbonate.

Although pyrite and calcite are uncommon minerals in the rocks that this study deals with, it is believed that the processes of hydrothermal alteration which took place at Pluma Hidalgo were essentially the same as those which have been described in the literature as propylitization,

in this case with accompanying sericitization. The differences are minor, mineralogically, and are simply due, it is believed, to the fact that the hydrothermal solutions, composed essentially of water, were poor in CO_2 and H_2S, and perhaps contained some potash.

Chapter III

Mineralogy

Description of Minerals

Antiperthite - Microantiperthite is a primary constituent of much of the country rock, including the country rock surrounding the Pluma Hidalgo deposit, although it is less altered and more common in ore samples. The composition of antiperthite from several samples of ore was determined by optical means. The plagioclase is calcic oligoclase to sodic andesine (An_{28} - An_{32}), untwinned, varying locally in composition, and ordinarily (see below) making up about 75% - 80% of the antiperthite. The remainder is microcline; this is probably sodic (i.e., strictly speaking, anorthoclase) since the indices of refraction are slightly higher than normal for microcline.

Grains as large as 1 cm. were seen, with the microcline lamellae, in the form of uniform rods and strings, up to about 0.1 mm. in width, but commonly finer. All the antiperthite shows evidence of granulation and strain, with undulatory extinction and bent lamellae being common. Alteration of antiperthite has been described in another section.

Some of the antiperthite contains microcline in quantities up to 40 - 45%, suggesting either that while the Na/Ca ratio was approximately constant in the original mixture, the K content varied, or, secondly, that some of the microcline is secondary and has replaced plagioclase. The second idea is supported by noting that in some samples where microcline is abundant, it occurs as irregular bands and patches with

little uniformity of orientation and often with a perthitic texture. That is, the plagioclase host is antiperthitic, but the microcline blebs themselves are perthitic, containing even smaller blebs of plagioclase (Figure 16).

H. L. Alling recognized that perthite can be formed either by exsolution or replacement of orthoclase by plagioclase, and he set up criteria on the basis of shape, orientation, etc., of the blebs for determining which process took place. In exsolution, the blebs are uniform and relatively small, in the form of stringlets, strings, rods, and beads. In replacement, the blebs are more irregular in shape, with not as much uniformity of orientation, and an obvious cutting of the host, especially near the margins. The blebs take the form of films, bands, plumes, and patches.[1] Probably the same criteria can be applied to antiperthite, and on this basis there is both replacement and exsolution in the antiperthite which was studied, although the latter process prevails. This would contradict Köhler, who claims that antiperthite can be formed only by replacement.[2] Dittler and Köhler performed a series of experiments in which microperthite was heated for 500 hours at 1000° C. The albite lamellae were absorbed (dissolved), and a homogeneous crystal was produced (cryptoperthite ?). However, antiperthite showed no change.[3]

None of the above is conclusive proof either of replacement or exsolution in antiperthite. Very little has been written on this mineral, since apparently it is relatively rare. In any case, it is one of the subjects in this paper which deserves further study. Chemical analysis will undoubtedly solve many of the questions.

Microcline - Microcline is present as small grains associated with granular plagioclase and antiperthite. The grains are both smaller and less numerous than the plagioclase grains, and are commonly seen surrounded by the latter.

Plagioclase - An oligoclase - andesine of composition varying from about An_{28} to An_{32} is present as small grains associated with antiperthite and microcline in both the country rock and the ore. It is believed that this feldspar, as well as the microcline,, is derived from the original antiperthitic rock, which was metamorphosed under conditions of heat, pressure, and rate of cooling which enabled it to recrystallize as microcline and plagioclase.

The oligoclase - andesine is commonly altered to clinozoisite and/or sericite, so that the nature of the feldspar which remains - if any - is hard to determine. It is suspected that it is quite sodic. There may even be albite present, as suggested by Ross, who presents the following equation,[4] where the altering solution is composed chiefly of water:

$$\left[\begin{array}{c} 8\ (Na_2O \cdot Al_2O_3 \cdot 6\ SiO_2) \\ 4\ (2\ CaO \cdot 2\ Al_2O_3 \cdot 4\ SiO_2 \end{array}\right] \text{Andesine} + 4\ (K_2O \cdot Al_2O_3 \cdot 6\ SiO_2) \text{ Microcline} + 3\ H_2O \text{ Water} = \left\{\begin{array}{l} 8\ (Na_2O \cdot Al_2O_3 \cdot 6\ SiO_2) \\ \text{Albite} \\ + \\ 2\ (H_2O \cdot 4\ CaO \cdot 3\ Al_2O_3 \cdot 6\ SiO_2) \\ \text{Clinozoisite} \\ + \\ 3\ (K_2O \cdot Al_2O_3 \cdot 6\ SiO_2) \\ \text{Microcline} \\ + \\ (H_2O \cdot K_2O \cdot 3\ Al_2O_3 \cdot 6\ SiO_2) \\ \text{Muscovite} \\ + \\ 4\ SiO_2 \\ \text{Quartz} \end{array}\right.$$

Quartz - Quartz is a common mineral in both the country rock and the ore. It occurs chiefly as elongated grains, commonly crushed, which are parallel to the foliation of the rock (Figure 11). Where it is macroscopic, much of it accounts for the gross gneissic character of the rock. In places, grains of rutile and apatite are seen in uncrushed quartz, and it is suspected that this quartz - as well as the rutilated quartz which is sometimes seen - is secondary and probably accompanied the mineralization.

Augite - Augite is present as a minor (relict) mineral in the ferromagnesian bands of the country rock and in more abundant quantities in the rock considered ore, particularly where the ferromagnesians make up a large amount of the rock. It always shows some alteration, sometimes to hornblende, sometimes directly to chlorite (Figures 19 and 20). Often all three minerals can be seen adjacent to each other. Alteration of augite along cleavage planes is common, giving the mineral a "patchwork" look. Augite is usually fractured, but alteration along fracture planes is not common. The crystals are euhedral to subhedral. The mineral is colorless to very pale brown, non-pleochroic.

Amphibole - A green hornblende, thought to be primary, occurs associated with augite. The most common variety shows pleochroism between light green and bluish green. N_x and N_z are equal to approximately 1.67 and 1.69 respectively. It alters to chlorite.

Uralite, a fine-grained, fibrous amphibole, is commonly found as an alteration product of augite. Its properties could not be determined beyond noting its light green color, apparent lack of pleochroism, and inclined extinction. It is probably a type of hornblende.

A colorless mineral, quite rare, is occasionally seen and is thought to be tremolite.

Chlorite - Chlorite is one of the commonest minerals in the rocks which were studied. It is seen as an alteration product of augite, amphibole, olivine, and biotite. It is seen replacing feldspar and quartz. Several kinds of chlorite are seen, often co-existing with each other and even intermixed. Because of this, and because they are all extremely fine-grained, it is quite difficult to determine the optical properties aside from the refringence and birefringence. Two ranges of refractive index seem to be the most common, these being 1.58 to 1.60 and 1.62 to 1.64. All chlorites show birefringence less than .010. The first range of refractive indices represents a group of chlorites with low iron content, and these may be alteration products of olivine, which, though not very common in the samples is known to be low in iron. Possibilities are antigorite (which is also a serpentine), jenkinsite, clinochlore, prochlorite, etc. The second group of chlorites are moderate in iron content and may represent alteration products of augite and hornblende. Possibilities are brunsvigite, diabantite, ripidolite, etc.[5]

One chlorite, which was seen in places in the ore, is clearly derived from biotite. It is pleochroic in green to very light yellow-green, and gives a deep blue anomalous interference color. It is probably penninite.

Muscovite and Sericite - Muscovite and its fine-grained equivalent, sericite, are common alteration products of the feldspars. Commonly the microcline is attacked first and more thoroughly, but sericite (or paragonite, its sodium equivalent) also attacks the plagioclase. Sericite often occurs with clinozoisite.

Muscovite which is well developed and easy to identify (although still microscopic) occurs associated with sericite. It commonly assumes a radial form (wedge-shaped or bowtie-shaped grains). It replaces feldspar (Figure 13).

Clinozoisite - Clinozoisite is a widespread mineral, although it was seen only microscopically. It replaces the feldspars, which acquire a "pock-marked" appearance from the disseminated microscopic grains and aggregates (Figure 12). Clinozoisite as intersticial material between feldspars is also quite common. It is sometimes seen as veinlets in feldspar (Figure 17), and in veinlets of chlorite, again in feldspar. The mineral shows anomalous interference colors of deep blue and, less commonly, greenish-yellow. It is colorless, but its high relief compared to the feldspars makes it outstanding.

Rutile - Rutile is a common mineral in the area, occurring in moderate to great concentration in the ore bodies and occasionally as small disseminated crystals in the common country rock. Where the disseminated crystals are of a certain abundance and size, or where the rutile is massive and abundant, the rock may be called ore. As crystals, rutile may be found in either a feldspar or a ferromagnesian groundmass, but it is more common in the former. A more complete description of the ore is given in the section on Petrography.

Rutile is almost always associated with ilmenite, though the latter may be minor compared to the rutile.

The color of rutile in hand specimens varies from dark red to dark reddish-brown. The luster varies from dull to metallic. In thin section,

the color is orange-brown; rarely, brown. There is little pleochroism. Twinning is common

Rutile grains contain numerous microscopic fractures, which apparently are never filled.[6]

Rutile replaces feldspar (Figure 22). It is sometimes seen replaced by ilmenite (Figure 23), but more commonly it appears that rutile and ilmenite were contemporaneous. Alteration of rutile to sphene is sometimes seen (Figure 25).

Ilmenite - Ilmenite is a widespread mineral, occurring commonly but in minor quantities in country rock, and in greater quantities, and often associated with rutile, in those rocks considered as ore. It is almost always associated with the ferromagnesian minerals, augite and hornblende, and is seen replacing them (Figure 11). It is often accompanied by apatite, which it replaces. One sample consisted entirely of ilmenite and apatite, with very minor chlorite and calcite.

Ilmenite is found in sizes ranging from microscopic grains to large masses made of grains $\frac{1}{4}$" or more in length. The mineralization is commonly found in a direction parallel to the foliation in the rock. The grains often have fractures which may be filled with chlorite and, less commonly, calcite (Figure 21). Ilmenite is found both enclosing and invading rutile. It is sometimes seen altering to sphene and leucoxene.

Apatite - Apatite is commonly associated with ilmenite and, less frequently, with rutile. It is found in grains ranging in size from microscopic to 4 or 5 mm (especially in ilmenite gneiss), in most places elongated in

the direction of foliation (i.e., mineralization). Apatite grains are commonly found within ilmenite (or rutile) or alongside it, and are seen cut by ilmenite (or rutile) veins. Apatite is commonly attacked by chlorite in fractures. In one specimen, the apatite is very altered by chlorite and calcite. This is unusual, considering the often-cited stability of apatite under conditions of alteration.

In hand specimen the apatite is a grayish-green. In thin section it is colorless. As noted, it is not commonly found in its usual six-sided prismatic habit, but rather in elongated grains. See Figures 10 and 21.

Minor Minerals

Clivine sometimes occurs associated with the other ferromagnesian minerals. Its optic figure is positive with a large 2V, indicating a low iron content (i.e., near forsterite). Alteration is commonly to chlorite (probably antigorite) but in places to serpentine (antigorite plus chrysotile ?). Olivine crystals are euhedral to subhedral, always very fractured and showing very poorly developed cleavage. It is colorless to light brown in thin section.

Calcite is found occasionally in ore smaples, particularly as veinlets cutting ilmenite and filling interstices between ilmenite and rutile. In one sample it replaces apatite. It usually shows well-developed rhombohedral cleavage. Calcite was also found in a veinlet of a mineral believed to be epidote (Figure 18).

Biotite is seen very rarely in hand specimens and under the microscope, and only in ore. In hand specimens it has a dark-brown, smoky

appearance. In thin section, it is light yellow-orange, pleochroic to dark brown-orange. It is seen altering to a chlorite which is probably penninite.

Garnet is encountered occasionally in the country rock. It was not seen in ore samples. Typically the garnets are small, usually less than 2 mm, and they seem to be more common in a feldspar matrix than in a ferromagnesian ore. All the garnet seen in thin section has been fractured and attacked in these fracture planes by chlorite, sericite, and clinozoisite.

Epidote (?) was found in only two specimens, as microscopic veins in feldspar. The mineral is colorless, shows very high relief, and interference colors (normal) up to low second order. In one case it is associated with calcite. It may be clinozoisite showing normal interference colors (Figure 18).

Serpentine (?) (other than antigorite) is found rarely as an alteration product of olivine and pyroxene. It is seen as either fine-grained or fibrous, with the fibers perpendicular to the interstice or grain boundary of the mineral it replaces, as in asbestos. It shows higher interference colors than any of the chlorites encountered, and it is pleochroic in green. It may be chrysotile. In places it contains microscopic crystals of pyrite.

Sphene is occasionally seen replacing rutile in the ore. Less commonly it replaces ilmenite. It is colorless to very light brown, slightly pleochroic in light brown. It is very fine-grained and is not found in its usual habit of euhedral rhombs (Figure 25).

Leucoxene is a rare alteration product of ilmenite and rutile. It is seen more often in very weathered rocks and is sometimes associated with sphene. It is white in reflected light.

Pyrite is rarely found as minute grains in the alteration products of augite and olivine.

Comparison with Deposits at Nelson County, Virginia

The mineralogy of the Pluma Hidalgo deposit is remarkably similar to that found in the disseminated titanium deposits at Nelson County, Virginia. Both the host rock and ore mineralization are approximately the same. C. S. Ross has written a complete and very commendable paper on these deposits, and he says:

> The titanium deposits in the central part of Virginia, near the eastern base of the Blue Ridge, have long been the world's principal source of rutile and contain large supplies of ilmenite. The ores are associated with the Roseland anorthosite, a rock composed of antiperthitic andesine. This feldspathic rock mass is roughly elliptical in shape, covers an area of about 22 aquare miles, and intrudes a gneissic quartz monzonite that forms the dominant country rock of the region. The anorthosite shows crushing and granulation throughout the area, and only locally are there uncrushed residual masses, rarely more than 1 foot in diameter, of the coarse-grained primary feldspar. This elastic structure is similar to that in other anorthosite masses.

> The titanium minerals occur in deposits of two distinct types--as disseminated deposits in the anorthosite and as veinlike or dikelike masses of a rock known as nelsonite, which is characterized by rutile and apatite. Most of these masses are within the anorthosite, but a few are outside of it. Associated with the anorthosite are a few intrusive dikes and numerous ferromagnesian lenses that have replaced anorthosite along shear zones.[7]

The minerals present at the Virginia deposits are described briefly:

Antiperthitic Andesine is considered the only primary mineral. It has an average composition of $An_{31.5}$. It has been granulated and crushed, and the grains have for the most part retained their antiperthitic texture.

Microcline occurs as blebs and lenses in antiperthite. A minor amount occurs as intersticial material between andesine grains. It makes up about 25% of the antiperthite.

Quartz is usually rutilated.

Clinohypersthene occurs in lenses in antiperthitic andesine. It is believed to be secondary, although before and not connected with the main mineralization. It replaces feldspar.

Clinozoisite occurs disseminated in feldspar as grains and aggregates, and also in veins.

Amphiboles. Hornblende occurs as an alteration product of pyroxene. Tremolite occurs as minute grains in feldspar.

Mica. Fine-grained sericitic muscovite, and in places coarse muscovite, replaces feldspar.

Rutile is common.

Ilmenite is common and replaces rutile.

Sphene is an alteration product of rutile and ilmenite.

Magnetite is often associated with ilmenite.

Apatite occurs in nearly rounded but not euhedral grains. It is associated with rutile and ilmenite, but earlier.

Minor minerals are mainly graphite, pyrrhotite, pyrite (which is formed during the alteration of pyroxene to hornblende), and calcite (which is nowhere abundant but widely distributed).[8]

Chapter IV

Origin of the Pluma Hidalgo Deposit

It is believed that the country rock, which acted as a host for the mineralizing solutions, originally consisted of oligoclase - andesine antiperthite, quartz, and ferromagnesian minerals, notably augite and hornblende. This rock underwent regional metamorphism; the minerals were segregated and most of the antiperthite was recrystallized as separate grains of oligoclase - andesine and microcline. The gneissic character of the rock is well developed in most areas, and here the banding is obvious and very little feldspar remains as antiperthite. In other areas the segregation is grosser, the bands are larger and less obvious, the feldspar is less granulated and less recrystallized, and fracturing and faulting are more evident. It is in these areas of the country rock where, apparently, the greatest concentration of ore is found.

Alternately, the ferromagnesian minerals may have been introduced after the antiperthite rock was emplaced. However, replacement of feldspar by the ferromagnesian minerals was not observed, except insofar as chlorite replaces feldspar as part of the process of propylitization. Perhaps any such replacement by the ferromagnesians is masked by the great amount of alteration of the rock. In any case, it is plain that the ferromagnesians are earlier than the ore mineralization.

The ore mineralization proceeded as follows:

Apatite is the earliest mineral. It is seen enclosed by and cut by veins of both ilmenite and rutile.

Ilmenite and Rutile are large contemporaneous, and usually occur

together, though ilmenite tends to predominate in the ferromagnesian part of the rock (from which it probably derived some iron), and rutile tends to predominate in the feldspars. In places, ilmenite replaces rutile, which probably indicates that the solutions became iron-rich towards the end.

The widespread, but minor, ilmenite mineralization throughout the more gneissic and finer-banded country rock of the area is due to the slow migration of titanium-rich solutions during the period of mineralization. Evidently these solutions preferred the ferromagnesian bands. Where the banding and gneissic character of the rock is grosser, and where deposition was aided by fractures and faults, which acted as channels for the solutions, massive deposition took place, giving rise to the rock known as ore.

Quartz is largely contemporaneous with the titanium minerals, but it may be slightly later as in several places where rutile and apatite are found in ungranulated quartz. However, it is not an abundant secondary mineral. In places it is rutilated.

Propylitization followed the ore mineralization. The solutions consisted essentially of water, with minor CO_2, H_2S and perhaps K_2O. The solutions account for secondary hornblende, sericite, clinozoisite, chlorite, calcite and epidote (?), the last two minerals being the latest.

A notable absence among the minerals is zircon. As it is a common mineral in sediments-- expecially heavy-mineral placer deposits--and quite resistant to alteration, its absense may be a point against those who would argue for a syngenetic origin for these deposits.

The origin of the ferromagnesian minerals and the later mineralizing solutions, as well as the mode of transportation of the titanium, are

problems which remain unsolved. With regard to the Nelson County deposits, Ross believes that the ferromagnesian lenses, which have replaced anorthosite (antiperthitic andesine) along shear zones, are offshoots of "a deep-seated intrusive mass which is the ferromagnesian differentiate of the same primary magma whose other fraction is represented by the anorthosite."[1] The later mineralizing solutions, rich in P_2O_5, F and some Cl and CO_2 were distilled residues from another magma. The titanium presumably was carried as TiF_4, "which was distilled over from a partly crystallized parental magma."[2] Ross implies that there is no connection between the parent magma of the anorthosite and the magma from which originated the mineralizing solutions.

It is left to this author to speculate that there may be a closer relation and association between the anorthosite (antiperthitic andesine), the ferromagnesians, and the latter titanium mineralization than was suspected by Ross. It must be more than coincidental that two widely separated deposits are so similar, first in the type of host rock, which in itself is quite rare, and second in the unusual mineralogical relationships. More detailed geologic work in the area and a better understanding of the field relations, as well as careful analysis of the rocks and minerals, will undoubtedly answer this and other questions which are raised elsewhere in this paper.

FIGURES

Figure 1. Typical gneissic country rock, showing white feldspar with quartz (crushed) and ferromagnesian bands. Approximately actual size.

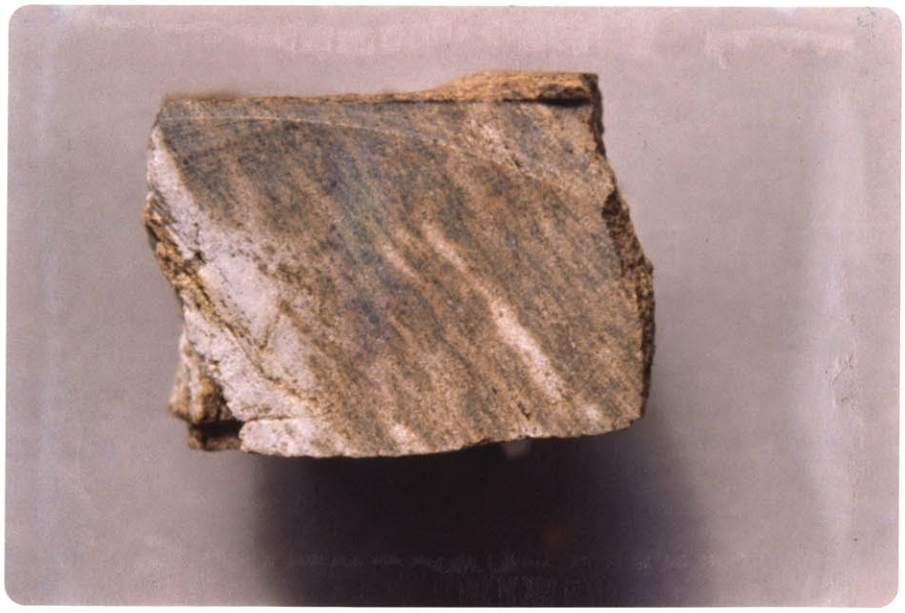

Figure 2. Sample of country rock with predominantly ferromagnesian minerals. Approximately actual size.

Figure 3. Split core of country rock. Note small grains of ilmenite at left. Approximately actual size.

Figure 4. Country rock, with fine quartz stringers. Small black grains at lower right are ilmenite. Approximately actual size.

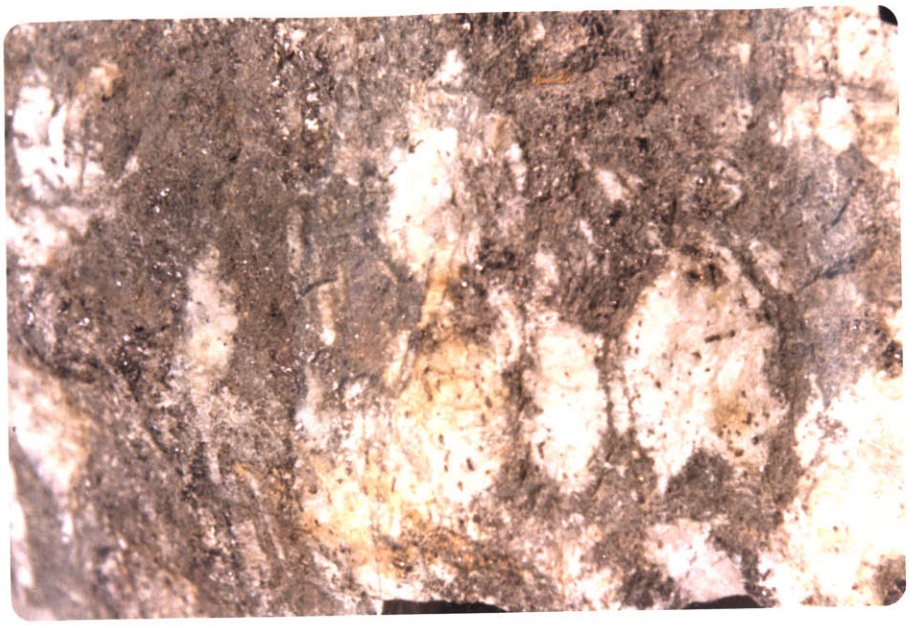

Figure 5. Ore, showing disseminated rutile and ilmenite in feldspar and predominant ferromagnesians. Note soaking and cutting of feldspar by chlorite, especially at upper left. Approximately actual size.

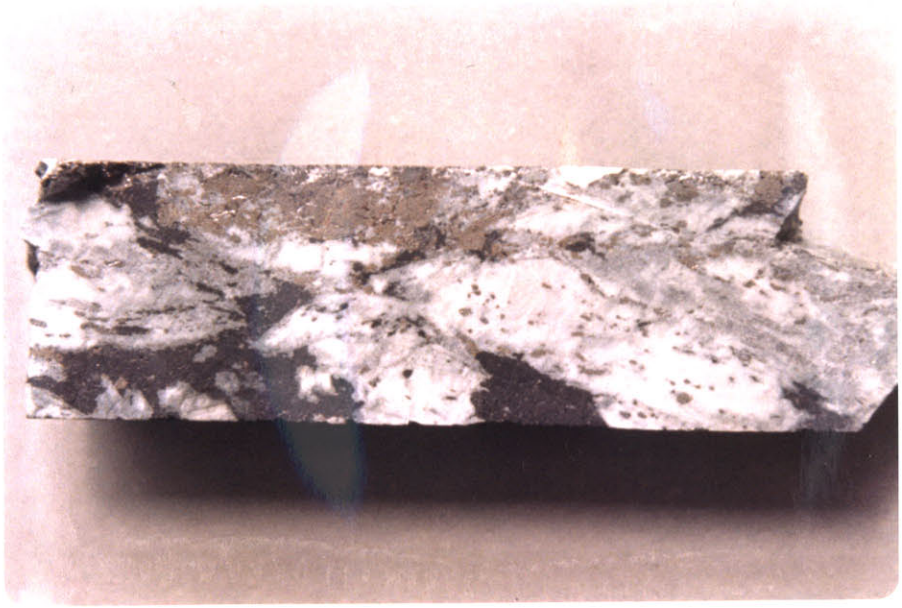

Figure 6. Split core of ore, showing rutile and ilmenite disseminated in feldspar, with associated ferromagnesians, mostly chlorite. Ilmenite at lower left is enclosing apatite. Approximately actual size.

Figure 5. Ore, showing disseminated rutile and ilmenite in feldspar and predominant ferromagnesians. Note soaking and cutting of feldspar by chlorite, especially at upper left. Approximately actual size.

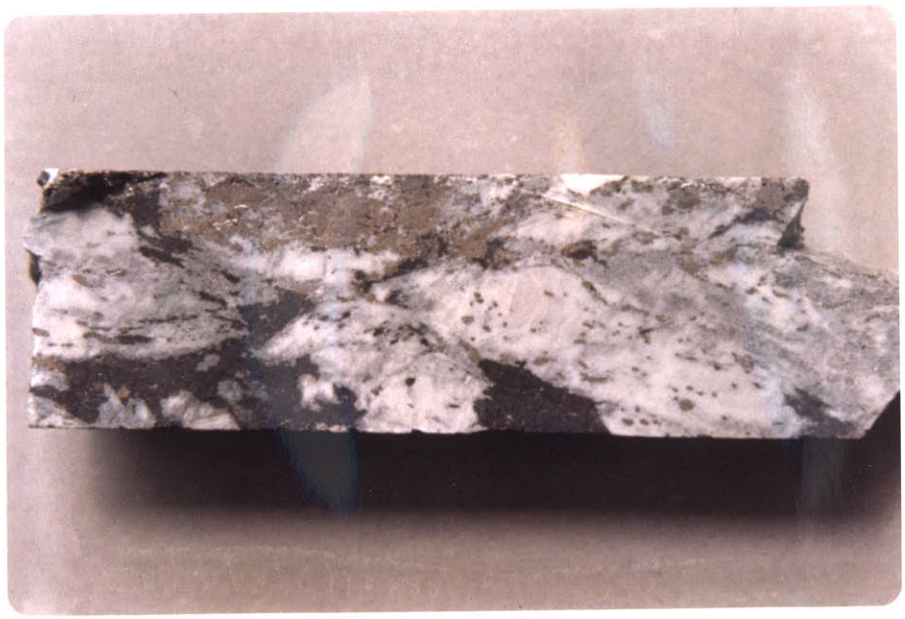

Figure 6. Split core of ore, showing rutile and ilmenite disseminated in feldspar, with associated ferromagnesians, mostly chlorite. Ilmenite at lower left is enclosing apatite. Approximately actual size.

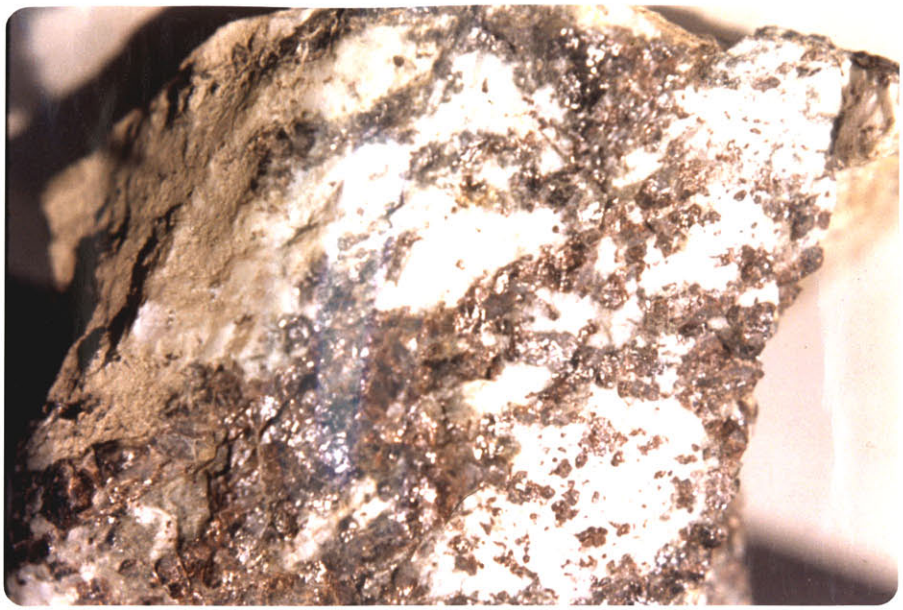

Figure 7. Ore, showing rutile disseminated in feldspar, with some ilmenite associated with ferromagnesians. Approximately actual size.

Figure 8. Polished section of ore. Rutile is seen in both feldspar and ferromagnesians. Approximately actual size.

Figure 9. Massive rutile ore, with feldspar showing much alteration by chlorite. Approximately actual size.

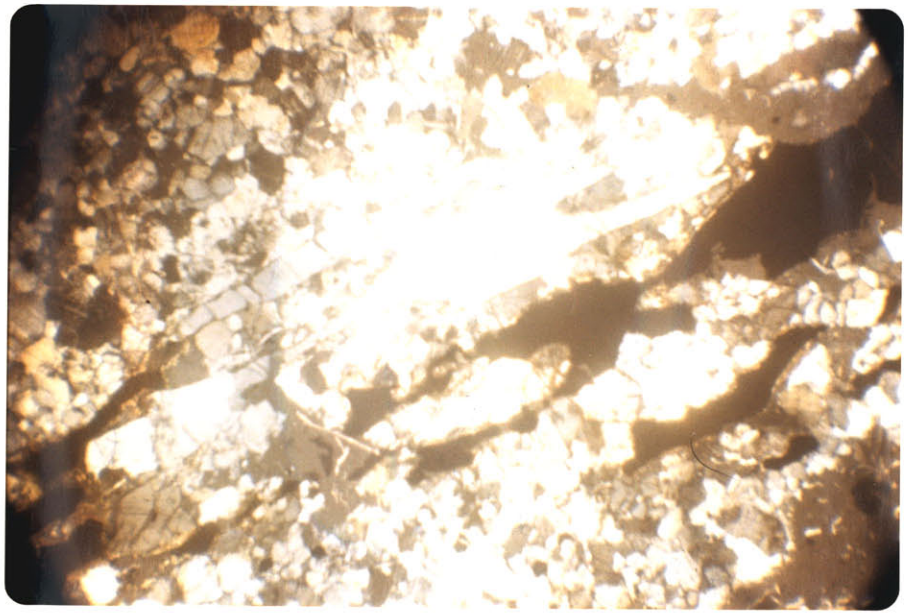

Figure 10. Photomicrograph of gneissic country rock, showing mineralization (ilmenite) parallel to foliation, elongated quartz grains, in a predominantly feldspar matrix, with some ferromagnesians (upper left). Crossed nicols, approx. X32.

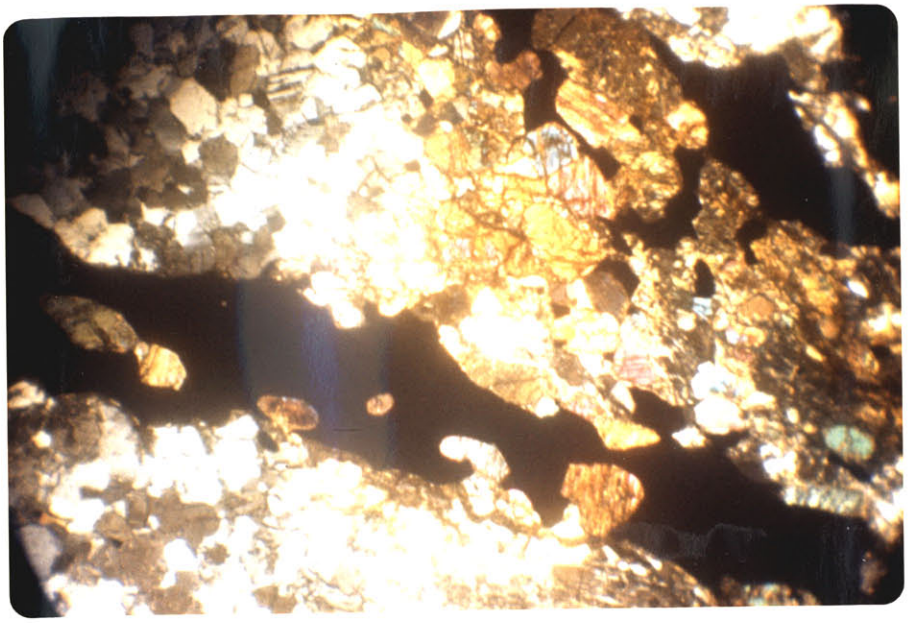

Figure 11. Photomicrograph of country rock, showing ilmenite replacing ferromagnesians in a granulated feldspar matrix. Alteration of ferromagnesians to chlorite is shown at upper right. Crossed nicols, approx. X32.

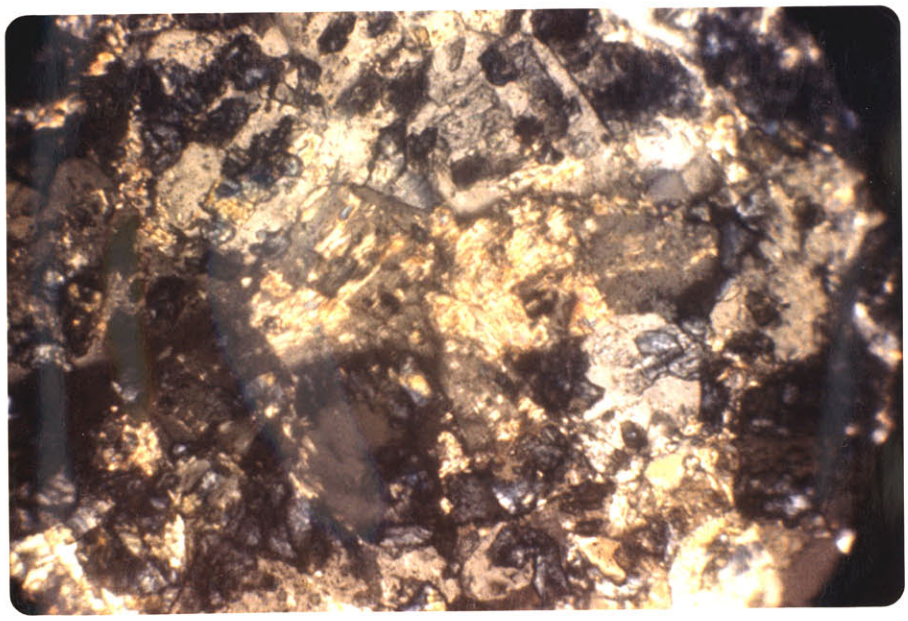

Figure 12. Photomicrograph showing granulated feldspar being replaced by clinozoisite (blue) and sericite. Crossed nicols, approx. X220.

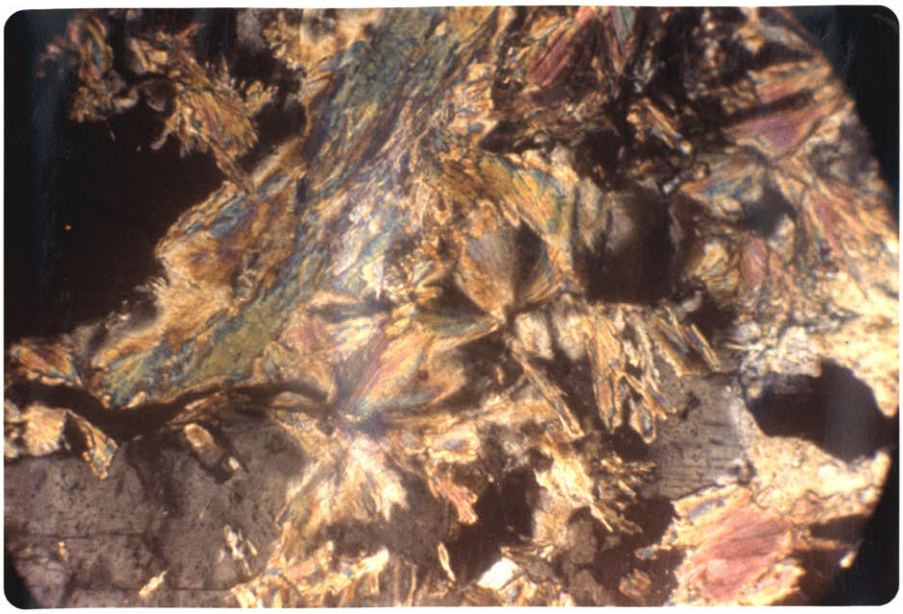

Figure 13. Photomicrograph showing sericite and well-developed muscovite replacing feldspar. Crossed nicols, approx. X220.

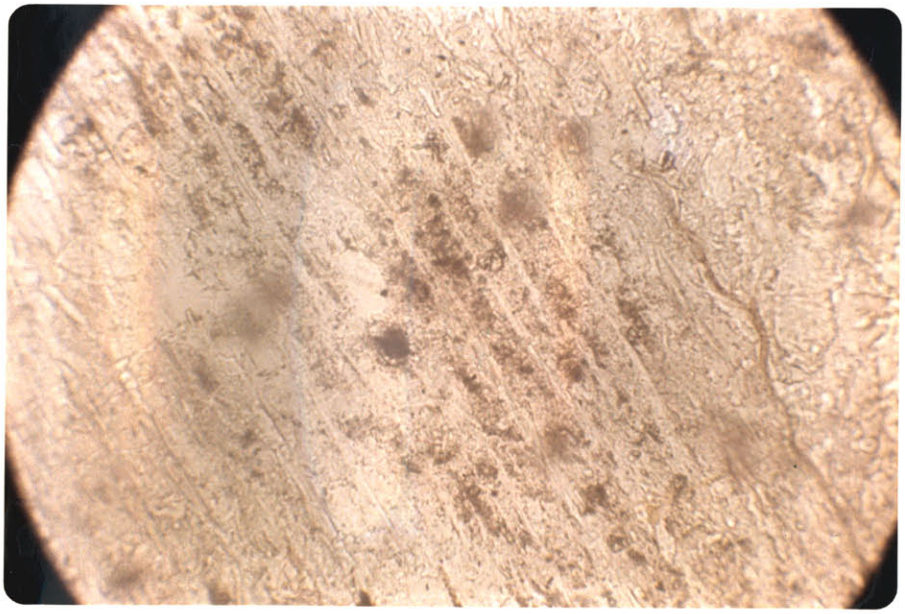

Figure 14. Photomicrograph of antiperthite, showing the oligoclase-andesine being selectively attacked by clinozoisite (dark patches). See Figure 15. Single nicol, approx. X220.

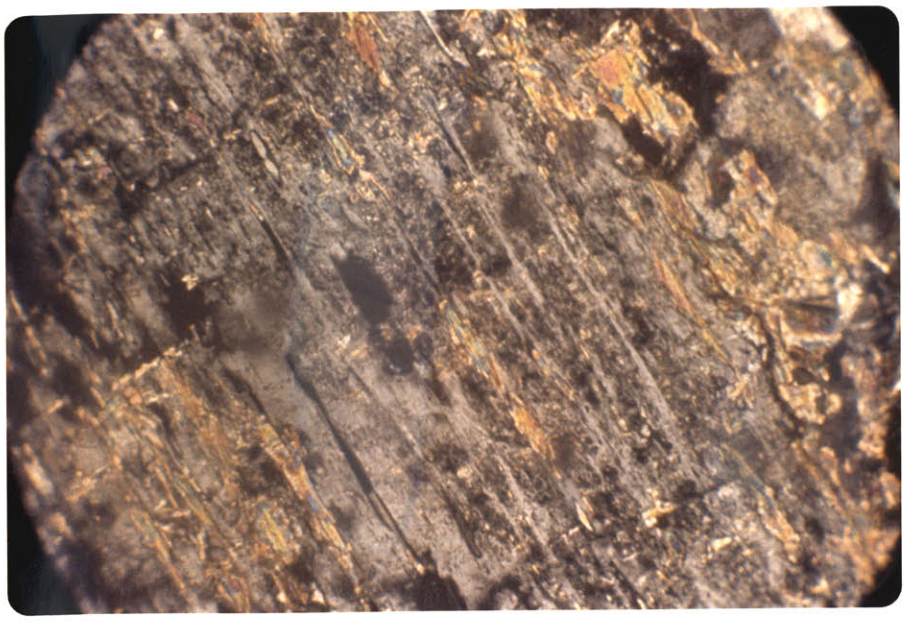

Figure 15. Same as Figure 14, with crossed nicols, showing the microcline of antiperthite being selectively attacked by sericite. Approx. X220.

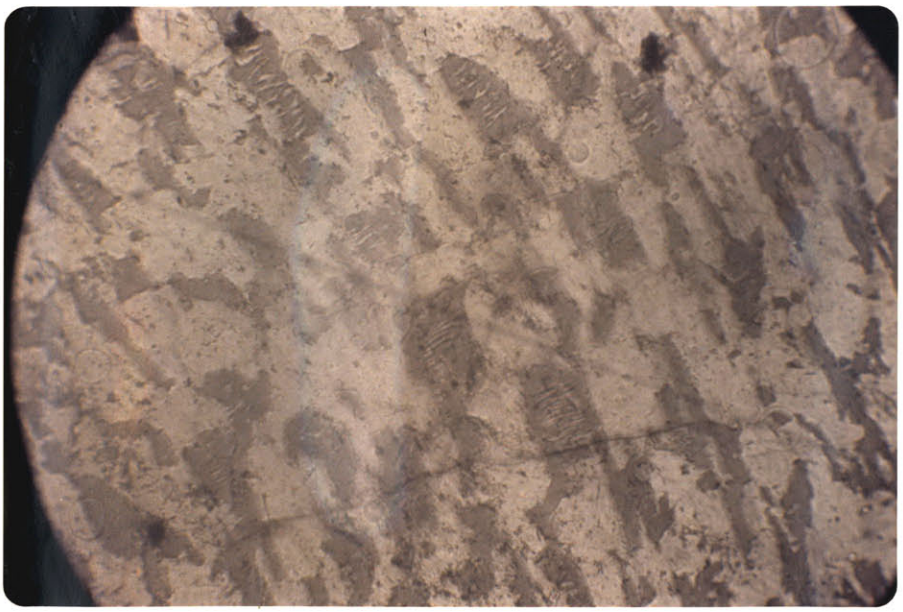

Figure 16. Photomicrograph of antiperthite, with the microcline blebs showing a perthitic structure. Crossed nicols, approx. X220.

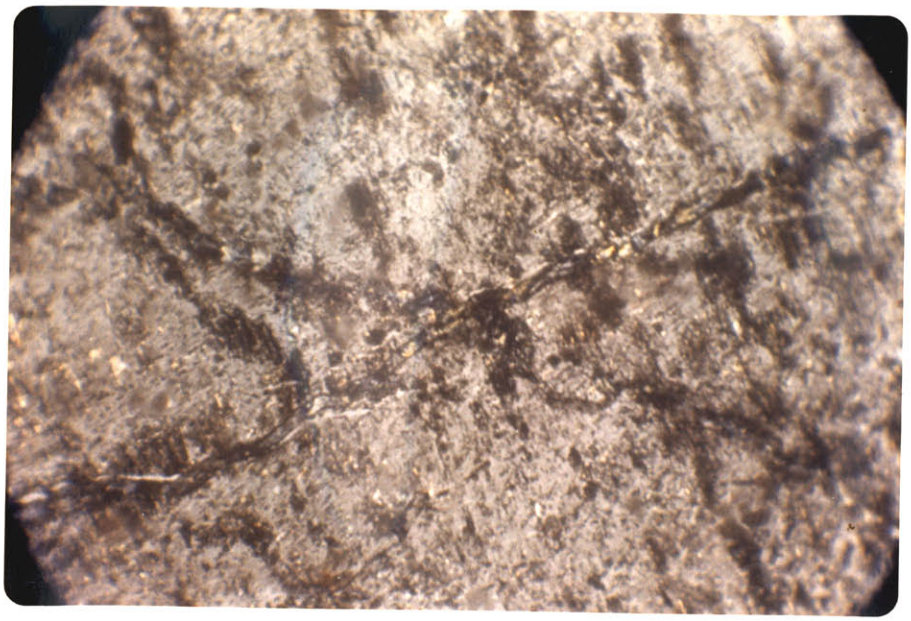

Figure 17. Photomicrograph showing clinozoisite veins in feldspar. Dark patches are also clinozoisite. There is some sericite at the left. Crossed nicols, approx. X220.

Figure 18. Photomicrograph of a vein of epidote (?) and calcite (white) in altered antiperthite. There are some ferromagnesians at the upper left. Crossed nicols, approx. X110.

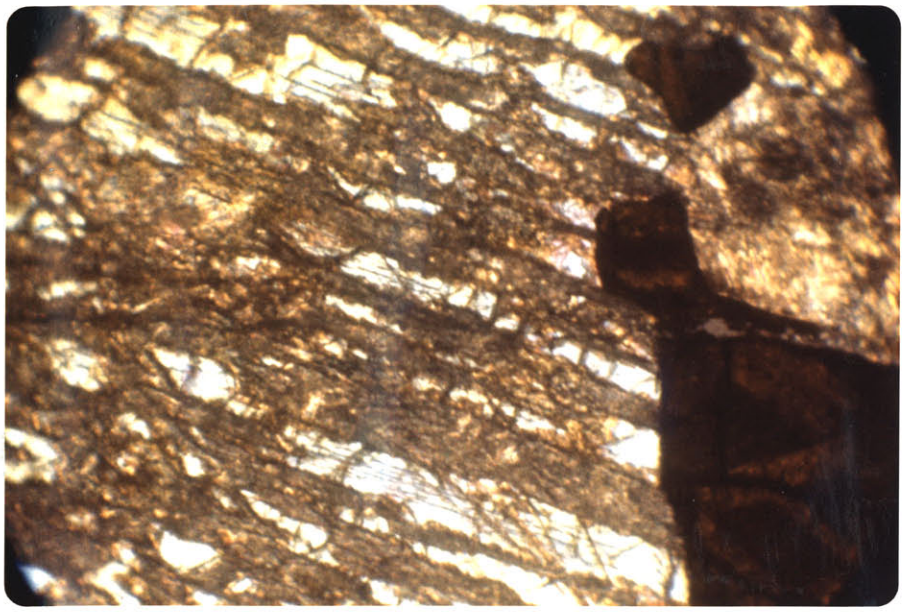

Figure 19. Photomicrograph of ore, showing augite (light blue) altering to chlorite along cleavage planes. Rutile at right. Crossed nicols, approx. X110.

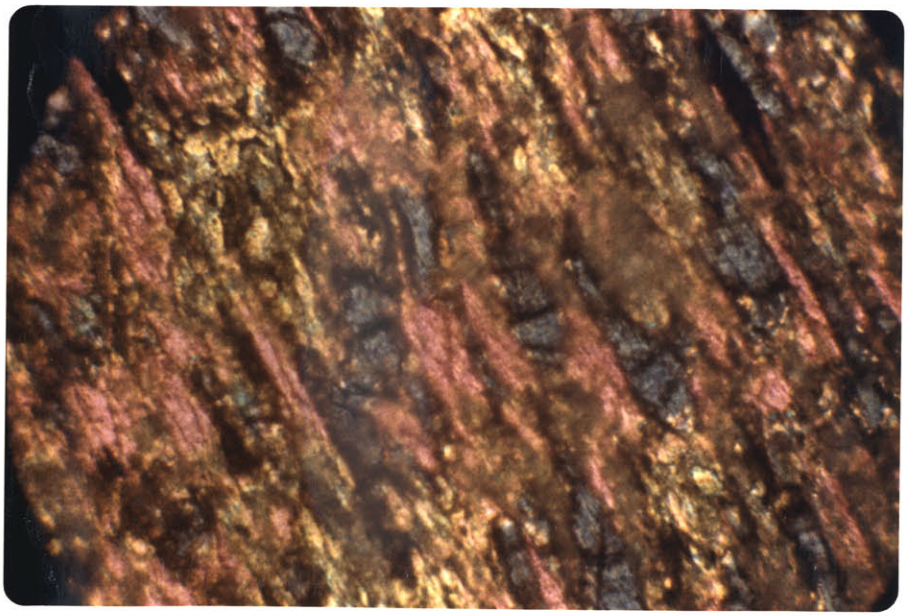

Figure 20. Photomicrograph showing augite (blue-grey) altering to hornblende (red), which in turn is altering to chlorite. Crossed nicols, approx. X220.

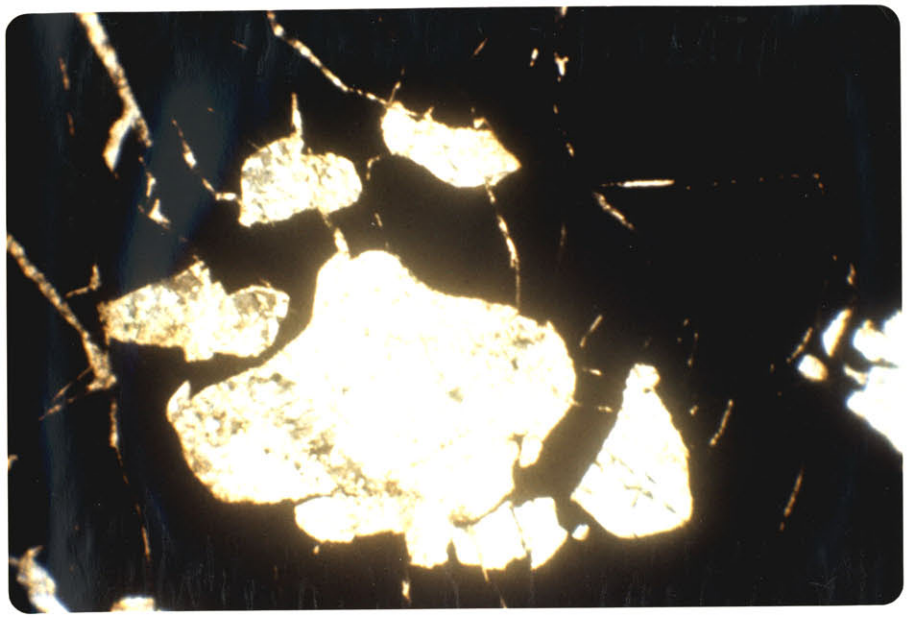

Figure 21. Photomicrograph of ore, showing apatite surrounded by ilmenite. The apatite has been altered by calcite, which also forms veinlets in the ilmenite. Crossed nicols, approx. X32.

Figure 22. Photomicrograph of ore, showing rutile replacing antiperthite. Grains at lower center and upper right are quartz. The other grains are granulated feldspar. Crossed nicols, approx. X32.

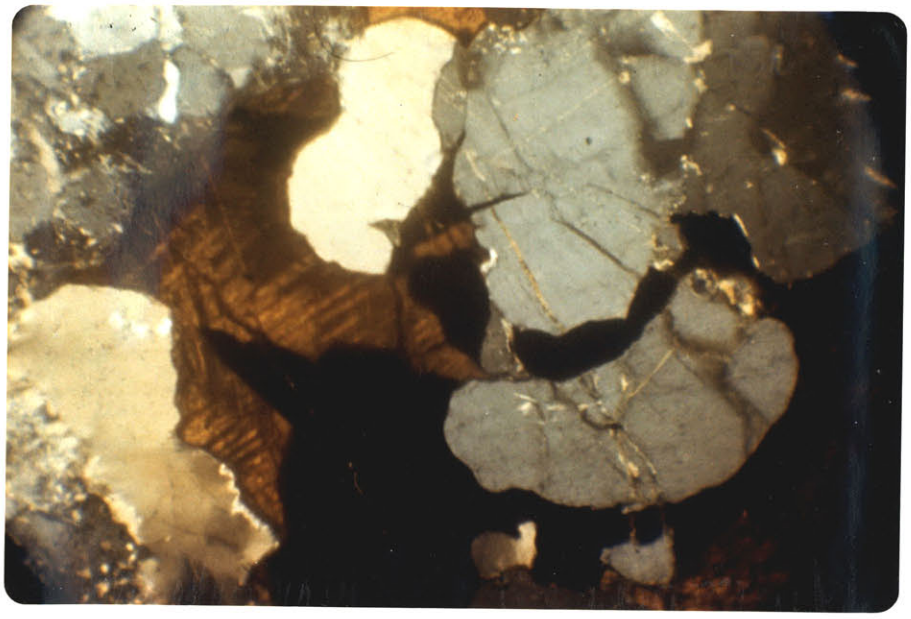

Figure 23. Photomicrograph of ore, showing ilmenite replacing rutile and enclosing apatite (grey). Light areas are quartz. Crossed nicols, approx. X110.

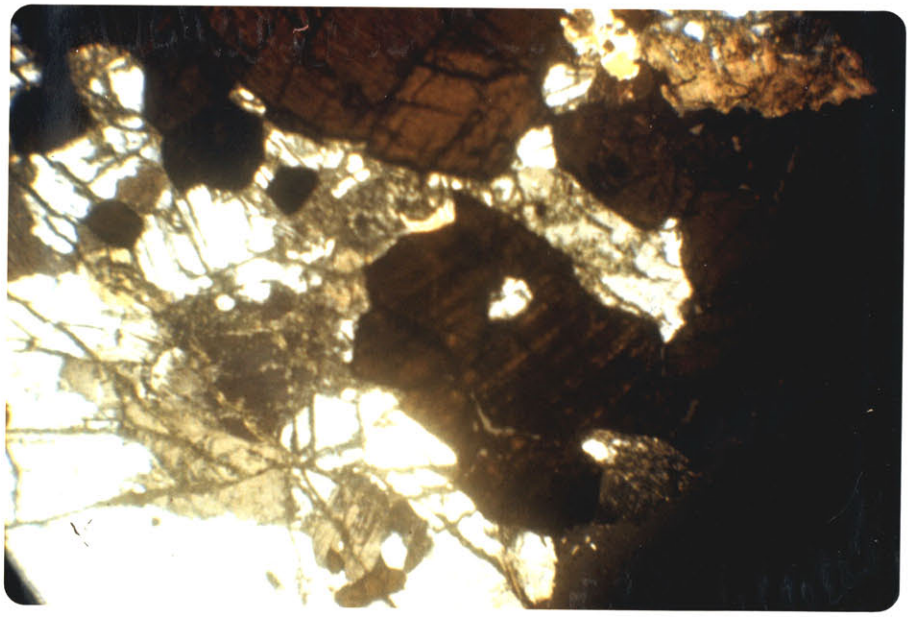

Figure 24. Photomicrograph of ore, showing antiperthite and granulated feldspar cut by chlorite veins. Orange grain at upper right is biotite. Crossed nicols, approx. X32.

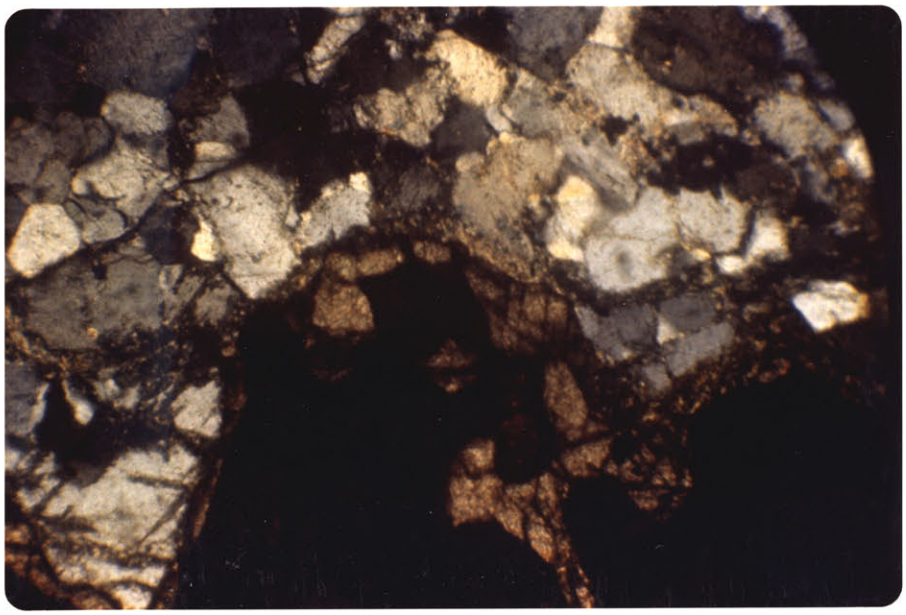

Figure 25. Photomicrograph of rutile (dark brown) altering to sphene (light brown) in a feldspar matrix. Crossed nicols, approx. X110.

Notes

Chapter I

1. - J. L. Gillson, "Titanium," In S. H. Dolbear, (ed.), Industrial Minerals and Rocks, A. I. M. E., 1949, p. 1044.

2. - J. González Reyna, Riqueza Minera y Yacimentos Minerales de México, México D. F., 1956, pp. 296 - 297.

3. - L. E. Lynd, "Titanium," In J. L. Gillson, (ed.), Industrial Minerals and Rocks, A. I. M. E., 1960, pp. 857 - 858.

Chapter II

1. - These areas are shown on maps supplied by the Republic Steel Corp. and are reproduced on Map # 2.

2. - Whether these blebs are actually exsolved material or are due to replacement of plagioclase is discussed in Chapter III, under "antiperthite."

3. - C. S. Ross, Occurrence and Origin of the Titanium Deposits of Nelson and Amherst Counties, Virginia, U. S. G. S. Professional Paper 198, 1941, p. 3.

4. - For a general description of charnockites and the granulite facies, see F. J. Turner and J. Verhoogen, Igneous and Metamorphic Petrology, 2nd Ed., New York, 1960.

5. - A. W. Groves, "The Charnockite Series of Uganda, British East Africa," Quarterly Journal of the Geological Society of London, Vol. 91, 1935, pp. 161 - 162.

Chapter II (continued)

6. - Ibid.

7. - F. D. Adams, "The Geology of Ceylon," Canadian Journal of Research, Vol. 1, 1929, p. 471.

8. - Ibid.

9. - Pentti Eskola, "On the Granulites of Lapland," American Journal of Science, Bowen Volume, 1952, p. 135.

10. - Ibid., p. 155.

11. - Republic Steel was interested in the manufacture of titanium metal, for which rutile is the preferred ore. The company had no use for the ilmenite.

12. - This is reported by many authors, for example:

a) Waldemar Lindgren, "Metasomatic processes in Fissure Veins," Transactions A. I. M. E., Vol. 30, 1900, p. 609.

b) G. M. Schwartz, "Hydrothermal Alteration of Igneous Rocks," Geological Society of America Bulletin, Vol 50, 1939, p. 193.

13. - Schwartz, op. cit., p. 195.

14. - Lindgren, op. cit., p. 645.

15. - Robert Coats, "Propylitization and Related Types of Alteration on the Comstock Lode," Economic Geology, Vol. 35, 1940, p. 3.

Chapter II (continued)

16. - L. E. Reber, jr., "The Mineralization at Clifton - Morenci," Economic Geology, Vol. 11, p. 564, 1916.

17. - Ibid. pp. 564 - 565.

Chapter III

1. - H. L. Alling, "Plutonic Perthites," Journal of Geology, Vol. 46 1938, pp. 142 - 147.

2. - A. Köhler, Mineralogical Abstracts, Vol. 10, 1948, p. 415.

3. - A. Köhler and E. Dittler, Mineralogical Abstracts, Vol. 3, 1926, pp. 79 - 80.

4. - Ross, op. cit., p. 32.

5. - A. N. Winchell, Elements of Optical Mineralogy, Part II: Description of Minerals, New York, 1951, pp. 381 - 389.

6. - According to Mr. E. F. Fitzhugh, jr., by personal communication, these microscopic fractures caused a 30% slime loss of rutile during the concentration process.

7. - Ross, op. cit., p. 1.

8. - Ibid., pp. 10 - 14.

Chapter IV

1. - Ross, op. cit., p. 1.

Chapter IV (continued)

2. - Ibid., p. 36. Ross found that many of the minerals at Nelson County were unusually high in flourine, which supports his conclusion.

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MAP # 1

INDEX – MAP SHOWING ROAD TO PLUMA HIDALGO

SCALE: 1" = [redacted]

GULF OF MEXICO

MEXICO, D.F.

VERACRUZ

PUEBLA

MEXICO

PAN AMERICAN HIGHWAY

OAXACA

ACAPULCO

PLUMA HIDALGO

PUERTO ÁNGEL

PACIFIC OCEAN

TO OAXACA

COPALITA

SAN ISIDRO

CAMPAMENTO

PLUMA HIDALGO

CANDELARIA

BUENA VISTA

RIO PLUMA

MAGDALENA

RIO CANDELARIA

RIO CHACALAPILLA

RIO TOLTEPEC

PROGRESO

APANGO

RIO MAGDALENA

TO PUERTO ÁNGEL

N

PLUMA HIDALGO REGION
OAXACA, MEXICO

SCALE: 1:60960 OR 1MM = 200'

LEGEND:

- MAIN ROAD
- OTHER ROADS
- RIVERS
- TOWN OR SETTLEMENT

EDWIN G. PAULSON
MAY, 1962

ADAPTED FROM MAPS SUPPLIED BY THE REPUBLIC STEEL CORP.

6"

MAP #2

PLUMA HIDALGO AREA
OAXACA, MEXICO

SCALE: 1" = [illegible]

LEGEND:
- ROAD
- RIVER
- ELEVATION
- SETTLEMENT
- KNOWN AREAS OF TI MINERALIZATION
- MAIN ORE DEPOSIT, MINA TISUR

EDWIN G. PAULSON
MAY, 1962

N

CAMP
▲3882'
PLUMA HIDALGO
(ELEV. 4365')
LA PROVIDENCIA
▲3500'
BUENA VISTA
▲2500'
▲2600'
EL JORDAN
▲3500'
SAN FRANCISCO
RIO JORDAN
RIO PLUMA
▲2700'
LAS MARGARITAS
3771'
PALO ALTO
▲3417'
GUADALUPE
RIO CHACALAPILLA
▲2500'
EL REFUGIO
▲2800'
DOLORES
▲2300'
▲2291'
LA MONTAÑA
▲2300'
INDEPENDENCIA
▲2300'
▲2000'
1400'
1300'
1200'
1100'
LA UNION
PROGRESO
▲2500'
RIO TOLTEPEC
▲1000'
LA ALIANZA
▲2900'
CONCORDIA
▲2300'
CERRO ESPINO
▲4575'
MONTE CRISTO
▲3100'
1400'
RIO MAGDALENA
1300'
RIO LA CABAÑA
LA JUNTA
1200'
1100'
EL CARMEN
▲2100'
1000'
APANGO

ADAPTED FROM MAPS SUPPLIED BY THE REPUBLIC STEEL CORP.